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Dielectrophoretic Filtration of Nonconductive Liquids

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Abstract

The filtration of liquids using highly nonhomogenous electric field was investigated. Very good results were achieved in removing metallic, ceramic, and plastic particles from practically nonconductive liquids.

INTRODUCTION

When a neutral particle is under the influence of a nonuniform electric field, a force is exerted on the particle. It is easy to understand the origin of this force. The particle becomes equivalent to a dipole p because of its polarizability, and since the field is nonuniform, a force exists which is equal to $\mathbf{F} = p\nabla E$. For this phenomenon, Pohl has coined the term "dielectrophoresis" (1). Practical applications of dielectrophoresis have been proposed and one can find several examples in Ref. 1. One of them is liquid filtration. It consists in flowing a dirty liquid in an inhomogenous electric field. If the dielectric permittivity ϵ_2 of the impurities to be removed is larger than the permittivity ϵ_1 of the liquid, it is possible to show (see the section entitled "The Dielectric Forces") that the impurities are attracted to the region of larger field gradient (if one supposes that the materials are perfectly insulating), and this gives the possibility to remove the impurities.

In Chapter 9 of Ref. 1 there is a detailed description of a very simple apparatus and its mode of operation. It is made by a cylindrical outer

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electrode and an inner electrode. If a voltage is applied between the two electrodes, it is known that a nonhomogenous field is created. The necessary condition for the appearance of a dielectrophoretic force is fulfilled. The liquid to be cleaned flows from top to bottom. If the dielectric constant ϵ_2 of the impurity particles is larger than the dielectric constant ϵ_1 of the fluid, the particles are attracted toward the region with the strongest field, i.e., toward the inner electrode, and the liquid is collected at the bottom of the apparatus. The successful application of the apparatus is determined by the yield: percentage of the trapped particles to the total amount of particles in the liquid before the filtration. Pohl and Schwar (2) got good results (yield of the order of 80%) under the following conditions:

- (1) Very slow flow rate (12.5 mL/min) and a waiting time before flow of 3 min.
- (2) Low diameter of the outer electrode (1 cm)
- (3) Relatively large value of the inner electrode diameter (1.5 mm). With a smaller radius the yield decreases although the field gradient increases
- (4) Low values of the particle concentration in the liquid (<10%)
- (5) Density of the liquid slightly larger than that of the particles

Point (3) is a little surprising because decreasing the inner electrode radius should give an increase of the field and its gradient. Consequently, we expect an increase of the yield. Pohl attributes this yield decrease to such phenomena as corona-like discharge and disruptive high conduction. We prefer to relate this effect to Point (4): the yield decreases if we increase the particle concentration. With an electrode of small radius, we have accumulation of particles near the electrode and an increase of the local concentration. In the case of a larger radius, one increases the collecting area of the inner electrode and we decrease the local particle concentration near this electrode. Even if this explanation is not the correct one, our feeling is that the yield is directly related to the area of the collecting electrode.

All the above conditions necessary to get a high recovery of particles are conditions good for laboratory research. They have, however, definite drawbacks for practical applications. In particular, we have to increase the flow rate and the radius of the outer electrode. But, since we cannot increase the dielectrophoretic force very much, we have to do two things: first, reduce the distance for a particle to be trapped, and second, increase the area of the collecting body. For that, we fill the space between the two electrodes by glass spheres which will act as collector bodies. Clearly these spheres will disturb the field lines, and in order to assure that the spheres will be attractive for the particles, their dielectric constant must be larger than that of the

liquid. We shall see that the field gradient is increased by the presence of the balls.

The purpose of this paper is to study the performance of such equipment in a cylindrical geometry with glass balls. In fact, such an apparatus exists in a commercial version (Gulf Oil Corp.), and we are interested essentially in understanding how it works and what are the improvements compared to the original apparatus of Pohl.

EXPERIMENTAL RESULTS

In Fig. 1 we give the general aspects of the apparatus. The basic part is a cylinder (diameter 5 cm, length 27 cm) which constitutes the outer electrodes. The cylinder is filled with glass balls. We used two kinds of balls with diameters of 3 and 6 mm respectively. The inner electrode is connected to the high voltage power supply while the outer electrode is grounded. In this work we used only the nonconducting liquid kerosene (heating oil). The liquid with a known quantity of powder flows through the main cylinder. In order to know the quantity of powder which is not trapped, the liquid is immediately filtered, as indicated in Fig. 1. The quantity of trapped powder is recovered by rinsing the cylinder several times with oil, without applying voltage. Below we shall show that the necessary condition for the particle trapping is $\epsilon_1 < \epsilon_2$. In our case, $\epsilon_1 \approx 2$. The permittivities of the different powders are given in Table 1 with other properties. All the permittivities are larger than 4 and consequently we observe trapping for all these powders. The yield is clearly a function of several parameters.

- (1) The properties of the powder, such as permittivity, conductivity (see the following section), density, and grain size (see Table 2).
- (2) The flow rate. In the majority of cases we used a flow rate of $18 \text{ cm}^3/\text{s}$. Since the volume of the liquid was 350 cm^3 , one experiment takes approximately 20 s. However, to check the influence of the flow rate, we have also investigated a flow rate of $30 \text{ cm}^3/\text{s}$.
- (3) The powder concentration. In this work we were interested only in a low concentration. As shown below, the yield is not dependent on the concentration in the range of interest.
- (4) The characteristics of the apparatus: Length, radius of the outer electrode, and radius of the inner electrode.
- (5) The characteristics of the glass balls: Permittivity (5.5) and radius of the balls. As already mentioned, we found almost no difference using two kinds of balls with different radii.

In Fig. 2 we present typical curves of yield versus applied voltage V for MgO powder at different concentrations. At $V = 0$ we have mechanical

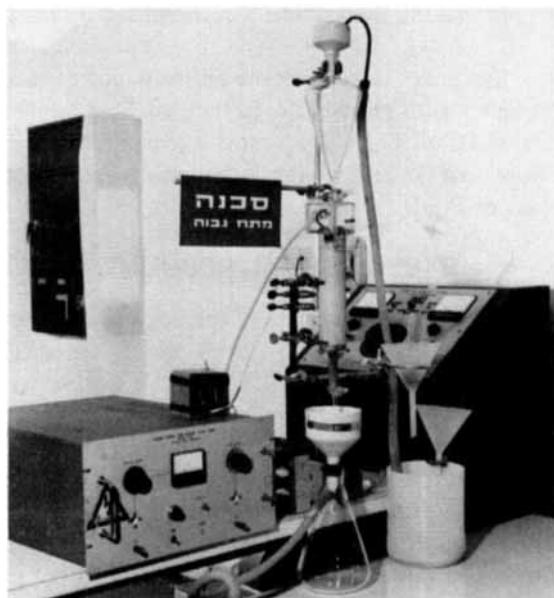


FIG. 1a. General view of the filtration apparatus.

yield. It can be an important fraction of the total yield (from 15 to 40%). Although we have not investigated this point, it can be an interesting advantage of the filtration system. By varying the voltage we first have a rapid increase of the yield and then a linear increase with V (with a slow slope). We note that the three curves of Fig. 2 are practically parallel, differing only by the values of the mechanical yield. This permits us to conclude that the electric yield is independent of the powder concentration (in the range of concentration chosen, below 0.5%).

In Fig. 3 we give the electric yield (total yield minus mechanical yield) for

TABLE 1^a

Material	ϵ	ρ (g/cm ³)	R (μ)	v_L (cm/s)	g_0	τ (s)	$L = v_T \tau$	t_c
MgO	9	3.6	35	0.68	0.54	3.5	8.5	11
Illmenite	33	4.7	44	1.5	0.79	12	27	8
PVC	4.5	1.3	50	0.24	0.23	2	4	13.6
Cu		8.95	35	2	1		27	7.2

^a ϵ (oil) = 2. ρ (oil) = 0.82 g/cm³.

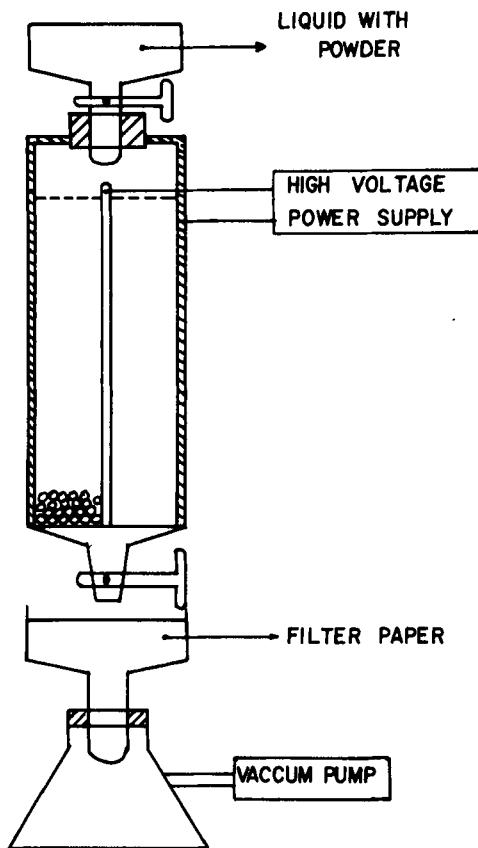


FIG. 1b. Filtration schema.

PVC, MgO, ilmenite, and copper powders. The shape of the curve is the same for all these cases. We shall discuss below the differences between these four curves as a function of the properties of the powders. At this stage we note that with this apparatus we get good yields for very different materials. The fact that they are below or of the order of 60% should not be considered as failure, since the filtration can be repeated several times. To check this point, we let the liquid with 2 g of MgO flow through the apparatus twice: the total yield was 70% in the first flow and reached 98% in the second flow. We have investigated the yield as a function of the radius of the inner electrode and of the flow rate. We varied the radius from 2 to 6 mm and found (Fig. 4) that at large voltage (6 kV) there are only minor variations of the yield with the radius. In Fig. 5 we have plotted yield versus voltage for

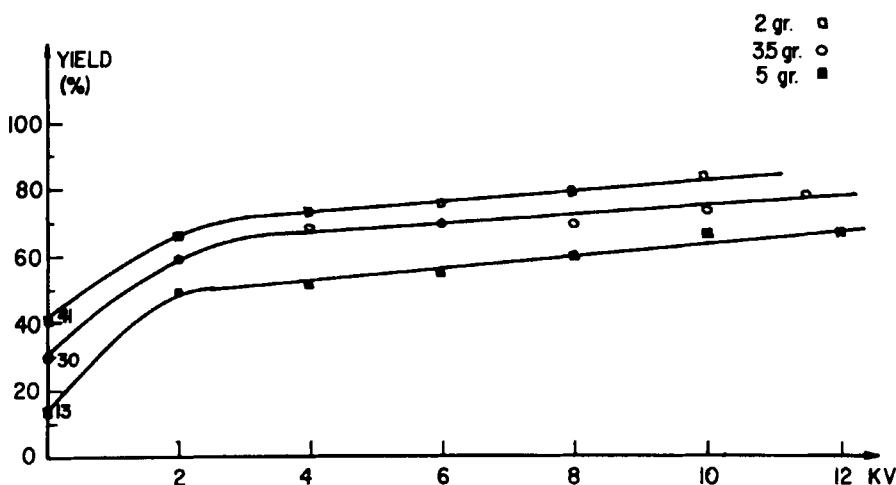


FIG. 2. Yield versus applied voltage for different MgO powder concentrations. Diameter of the balls: 3 mm. Diameter of the inner electrode: 8 mm.

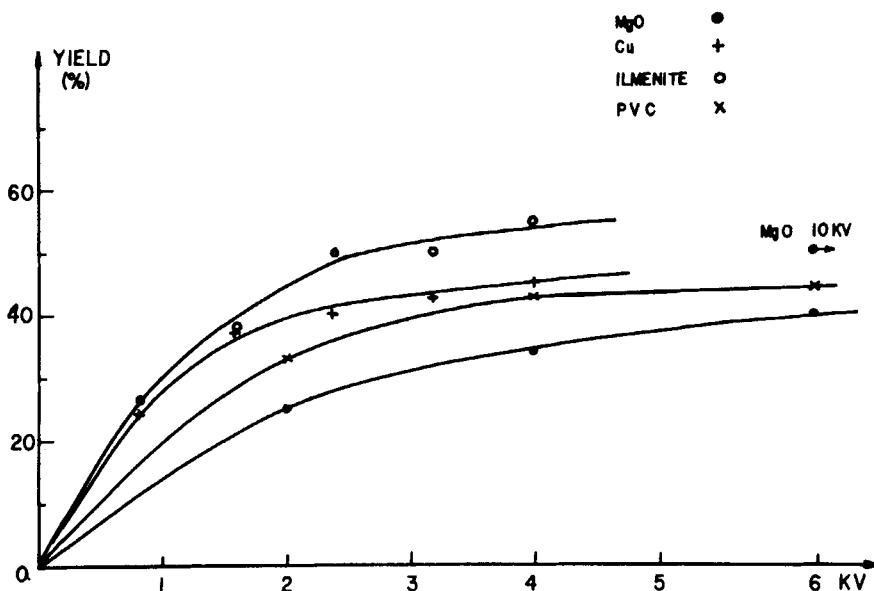


FIG. 3. Electrical yield versus applied voltage for different powders. Diameter of the balls: 3 mm. Diameter of the inner electrode: 8 mm.

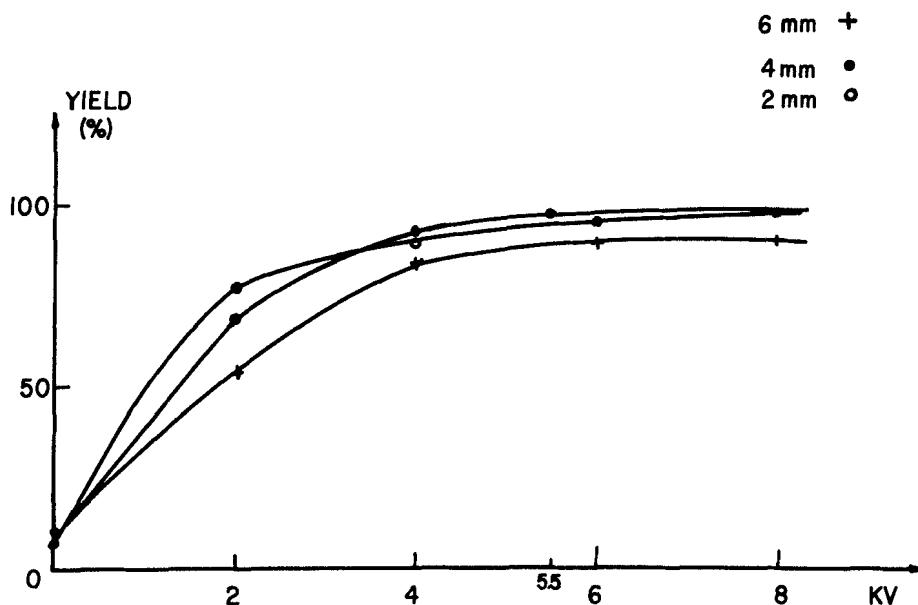


FIG. 4. Yield versus applied voltage for different inner electrodes with various diameters. MgO powder. Diameter of the balls: 6 mm. Note the larger values of the yield compared to Fig. 2. This is due essentially to the smaller radius of the inner electrode.

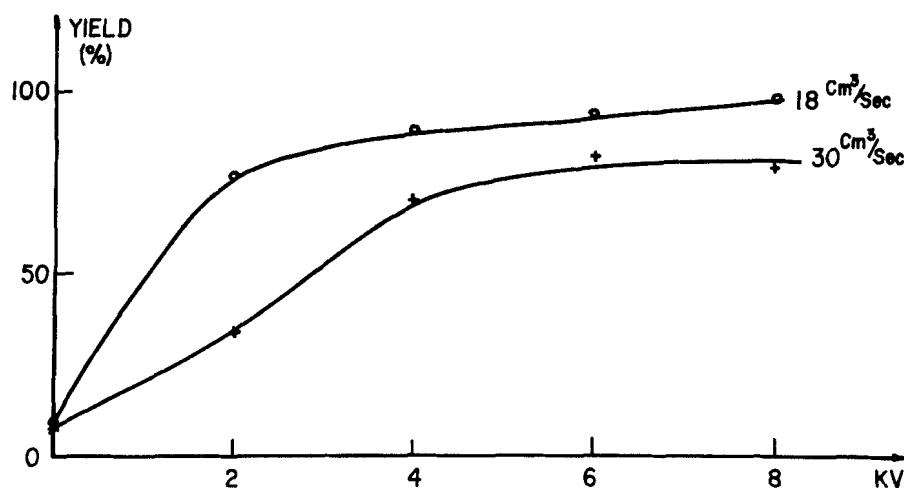


FIG. 5. Yield versus applied voltage for different flow rates. MgO powder. Diameter of the balls: 6 mm. Diameter of the inner electrode: 2 mm.

two different flow rates. As expected, increasing the flow rate from 18 to 30 cm³/s, decreases the yield significantly.

THE DIELECTRIC FORCES

The force acting on a spherical particle (radius R) of conductivity σ_2 and permittivity ϵ_2 embedded in a fluid of conductivity σ_1 and permittivity ϵ_1 due to a nonhomogenous field has been calculated by Molinari and Viviani (3) to be

$$F = 4\pi R^3 \epsilon_1 [E(t)*f(t)] \nabla(E) \quad (1)$$

In (1), $*$ denotes the convolution product:

$$E(t)*f(t) = \int_{-\infty}^t E(t)f(t-\tau) d\tau$$

and the function f is given by

$$f(t) = \frac{\epsilon_2 - \epsilon_1}{\epsilon_2 + 2\epsilon_1} \delta(t) + 3e^{-(\sigma_2 + 2\sigma_1)/(\epsilon_2 + 2\epsilon_1)t} \frac{\epsilon_1\sigma_2 - \epsilon_2\sigma_1}{(\epsilon_2 + 2\epsilon_1)^2} U(t) \quad (2)$$

with δ the Dirac function and $U(t)$ the unit step function. If we suppose that the functional dependence of E with x and t is of the form $E = E_1(t)E_2(x)$, we get:

$$F = 2\pi R^3 \epsilon_1 [E_1(t)*f(t)] E_1(t) \nabla E_2^2$$

or

$$F = 2\pi R^3 \epsilon_1 g(t) \nabla E_2^2$$

with

$$g(t) = [E_1(t)*f(t)] E_1(t) \quad (3)$$

Thus the force F depends on

- (1) The function $g(t)$ which appears explicitly through the properties of the fluid and of the particle (through ϵ_2 , ϵ_1 , σ_2 , and σ_1).
- (2) The field gradient

We shall study these two terms separately.

Influence of the Material Properties

We calculate the function $g(t) = [E_1(t)*f(t)]E_1(t)$ in the case of a dc field, i.e., $E_1(t)$ is constant and equal to 1. We get

$$g(t) = \frac{\epsilon_2 - \epsilon_1}{\epsilon_2 + 2\epsilon_1} + 3 \frac{\epsilon_1\sigma_2 - \epsilon_2\sigma_1}{(\epsilon_2 + 2\epsilon_1)(\sigma_2 + 2\sigma_1)} (1 - e^{-t/\tau}) \quad (4)$$

with $\tau = (\epsilon_2 + 2\epsilon_1)/(\sigma_2 + 2\sigma_1)$. This quantity is the relaxation time characteristic of the system. If $t \ll \tau$, then $g(t) = (\epsilon_2 - \epsilon_1)/(\epsilon_2 + 2\epsilon_1)$ and the conductivities σ_1 and σ_2 do not appear in the force, as in the case where $\sigma_1 = \sigma_2 = 0$. Now if $t \gg \tau$, then $g(t) = (\sigma_2 - \sigma_1)/(\sigma_2 + 2\sigma_1)$ and in this case the force does not depend on the dielectric constants ϵ_1 and ϵ_2 . We see that depending on the relative values of ϵ_1 and ϵ_2 , σ_2 and σ_1 , we can have very different values of the force for $t \ll \tau$ and $t \gg \tau$. In particular, it is possible that the force changes its direction with time as, for example, if $\epsilon_2 > \epsilon_1$ but $\sigma_2 < \sigma_1$. For more details see Refs. 4 and 5.

The Field Gradient

The determination of the field gradient in such a system is not directly possible. Without glass balls we can easily compute it, but the introduction of the balls seriously perturbs the field distribution and hence the field gradient. We are forced either to calculate it using a specific model or to find an analogous system on which we can do measurements. We chose the second possibility in an electrolytic tank. The analogy is not complete for the following reasons: (a) The real system is three dimensional and the analogous one is two dimensional. (b) The real system is disordered, and it is difficult to realize the analoguousness of disordered systems. Nevertheless, we think that the results we obtained are very suggestive and can take them as a qualitative determination of the field gradient.

In the electrolytic tank we measure the voltage distribution of a system made of two electrodes (two concentric circles). In the space between the electrodes we place stainless steel disks (which are analogous to the glass balls) in a close, compact arrangement and we fill the free space between the two electrodes with ordinary water (Fig. 6). This is an electrodynamic simulation of our real electrostatic system (all the relative dimensions are similar to the real system). Using a probe, we measure the voltage at several points in the interval between three contiguous disks. As explained in the

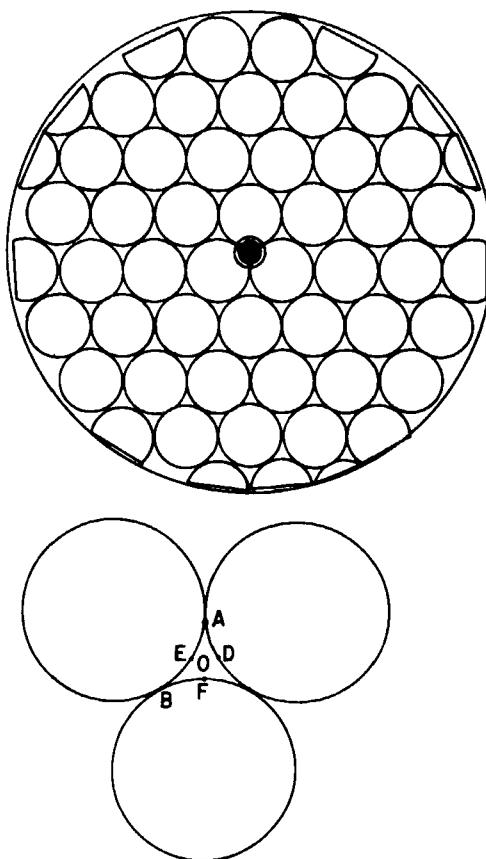


FIG. 6. Disposition of the stainless steel disks in the electrolytic tank.

Appendix, from these measurements we get an analytic expression $V(x, y)$ for the voltage in this interval. Then we calculate the quantity $F_0 = [(\partial E^2 / \partial x)^2 + (\partial E^2 / \partial y)^2]^{1/2}$ which is the absolute value of ∇E^2 . We plot this quantity for several points located along some chords in the space between the electrodes (Figs. 7a, 7b, 7c). In the same figures we give the calculated variation of $F_0 = (dE^2 / dr)$ for the case without disks. One sees that the experimental points are near the continuous calculated lines. But the important point is the ratio of the measured values (with disks) to the calculated ones (without disks). For points located near the central electrode (Fig. 7a), this ratio is 100–150, but for the remote points (Fig. 7b) this ratio is near 500–1000. Thus we have a strong enhancement of the force, and it becomes larger and larger when one goes toward the outer electrode. This

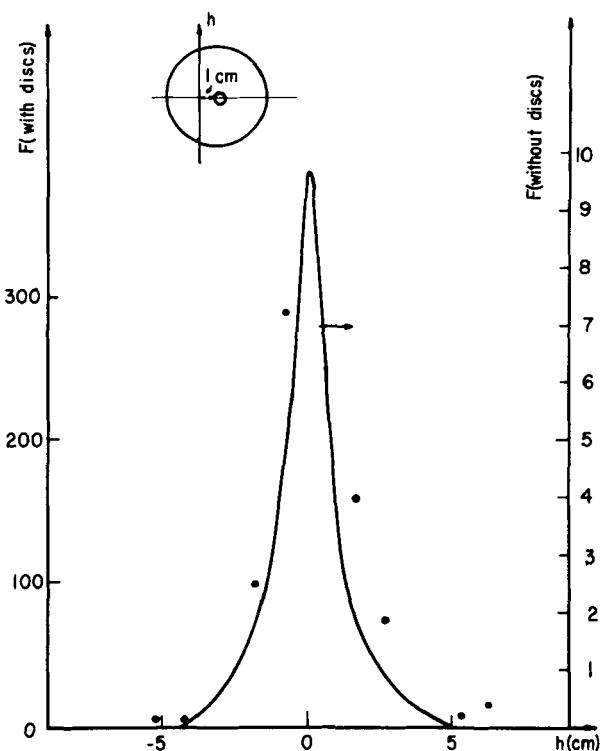


FIG. 7a. Absolute values of ∇E^2 . The points are obtained from measurements in the electrolytic tank. The line is calculated and corresponds to the case without balls along a chord located 1 cm from the center.

means that in this system the introduction of disks (or balls in the real system) gives a better field distribution than without disks from the point of view of getting large gradients in the whole apparatus. However, we have to remember that the values we get for the enhancement of the force is only for the analogous system. The conductivity ratio (between stainless steel and water) is above 10^3 , and in our apparatus the permittivity ratio is only 3. The enhancement in the real system is certainly very much lower. We conclude that in the real system there is a small increase of the force, especially near the outer electrode.

In the above results the dielectrophoresis force was calculated at the point O (see Fig 6) at the center of the triangle made by the three contact points of three disks (points ABC in Fig. 6). If we now compare the values of the force at these three points, we find that in the large majority of cases the force is larger near the points ABC than that at point O . This means that a particle

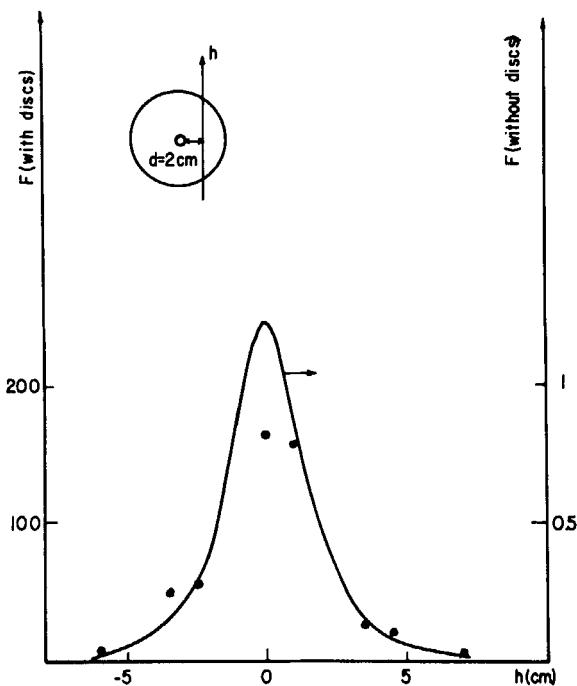


FIG. 7b. As for Fig. 7a but along a chord 2 cm from the center.

will almost always drift toward the balls and be trapped if the force is such that its direction is toward the strongest field gradient (i.e., $\varepsilon_2 > \varepsilon_1$ at $t \ll \tau$ or $\sigma_2 > \sigma_1$ at $t \gg \tau$). But if the direction of the force is such that the particle is drifting toward the lowest value of the field gradient, it will move to point O and the particle will not be trapped.

DISCUSSION

In this section we intend to discuss the results presented in Fig. 3 in order to understand the variations of the yield with the materials. We saw above that for $t \ll \tau$, $g = (\varepsilon_2 - \varepsilon_1)/(\varepsilon_2 + 2\varepsilon_1)$ but for $t \gg \tau$ we have $g = (\sigma_2 - \sigma_1)/(\sigma_2 + 2\sigma_1)$. The only situation for which these two expressions are identical is in the case of a metallic particle (here, copper). In the other case we have a relaxation time equal to $(\varepsilon_2 + 2\varepsilon_1)/(\sigma_2 + 2\sigma_1)$. If we suppose $\sigma_1 \gg \sigma_2$ (for example, for PVC $\sigma_2 \approx 10^{-12} \Omega^{-1} m^{-1}$ and for oil $\sigma_1 \approx 10^{-10}$ to $10^{-11} \Omega^{-1} m^{-1}$) we get (depending on the material), $\tau \approx 2$ to 12 s. For $t \lesssim \tau$, since $\varepsilon_2 > \varepsilon_1$, trapping will take place, but for $t \gtrsim \tau$, since $\sigma_2 < \sigma_1$, there will be no

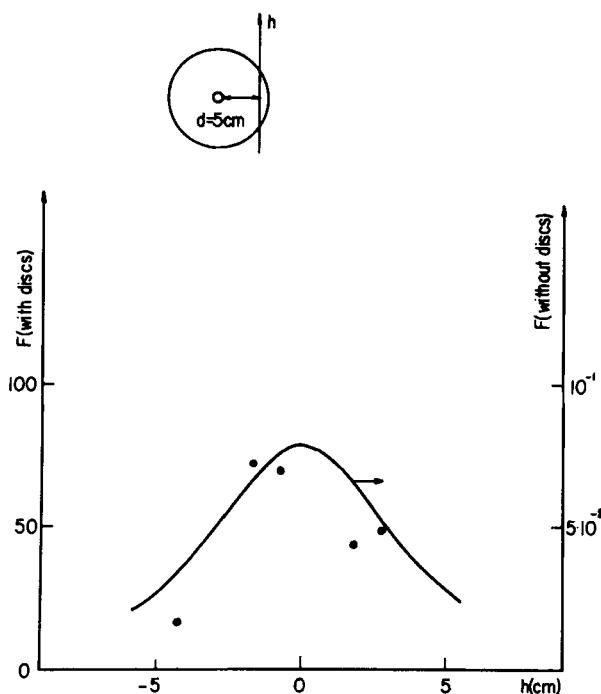


FIG. 7c. As for Fig. 7a but along a chord 5 cm from the center.

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trapping. This relaxation time has to be compared to the time for one grain to cross the apparatus. The velocity of a grain is equal to the velocity of the fluid plus the velocity of a grain relative to the fluid. We evaluate the velocity of the fluid as equal to 1.75 cm/s. For the relative velocity we suppose that the flow is not turbulent and we use the Stokes expression for the velocity

$$v_L = \frac{2}{9} \frac{R^2 g}{\eta} \Delta \rho$$

g is the gravitation constant, η the viscosity, and $\Delta \rho$ the difference in the densities. Taking $\eta \approx 1$ cps, we get the values of v_L reported in Table 1. Thus we can calculate the crossing time t_c . We see that for MgO and PVC, we have $t_c > \tau$ but for illmenite $t_c < \tau$. We can also define an effective length $L = v_T \tau$ in which the force is proportional to $(\epsilon_2 - \epsilon_1)/(\epsilon_2 + 2\epsilon_1)$ (v_T is the total velocity of the grain). The values of L are reported also in Table 1 (for Cu we take $L = \text{apparatus length}$).

In order to compare the results of Fig 3, we have to remember three main factors:

- (1) The factor $g_0 = (\epsilon_2 - \epsilon_1)/(\epsilon_2 + 2\epsilon_1)$
- (2) The effective length L , or the relaxation time τ
- (3) The difference $\Delta\rho$ between the density of the grain and that of the fluid

First, we compare the results for Cu and illmenite for which the effective length is equal to the apparatus length and the factor g is large. This explains why we get the largest value of yield for these two materials. However, although we have g (illmenite) $< g$ (Cu), we see from Fig. 3 that the yield of illmenite is larger. We think that this can be explained by the density difference which is much lower for illmenite than for Cu. It is clearly a favorable situation for particle trapping. PVC and MgO are characterized by $\tau < t_c$. This means that only for a time approximately equal to τ , the factor g is equal to its value at $t = 0$. For time larger to τ , g is given by $(\sigma_2 - \sigma_1)/(\sigma_2 + 2\sigma_1)$, and since $\sigma_2 < \sigma_1$, g is negative, i.e., no trapping. However, we get good values of the yield, especially for PVC, for which g and τ are relatively small. This is possible only if the trapping is very easy when $t < \tau$. Here too we think that the density difference may offer the explanation. This density difference in PVC is very low, $\Delta\rho \approx 0.48$, and for MgO it is $\Delta\rho = 2.78$. As above, a low value for $\Delta\rho$ is very favorable for the particles to be trapped.

CONCLUSION

This study shows that one can very easily remove impurities from liquid by dielectrophoresis. We saw that the yield is satisfactory for all types of impurities we investigated. However, we restricted our study to non-conductive liquid. Even in this situation we noted that it is necessary to take into account the low electrical conductivity of the liquid in order to understand the trapping phenomenon.

APPENDIX

In Fig. 6 we show the disposition of the disks in the electrolytic tank between the two circular electrodes. This is the simulation of our real system. We apply an ac voltage of 12V between the two electrodes. In the space between three disks we measure by means of this probe the voltages at the points *OABCDE* and *F*. We suppose that the potential around the point *O* can be expanded as

$$V = V_0 + ax + by + cx^2 + dy^2 + fxy \quad (1A)$$

Since $\Delta v = 0$, we have $c = -d$ and (1A) becomes

$$V = V_0 + ax + by + c(x^2 - y^2) + fxy \quad (2A)$$

From the values of V at the points *OABCDE* and *F*, we can calculate the values of V_0 , a , b , c , and f for the intervals between the three disks. We have more measurements than the unknown constants, and this gives us the possibility of checking the consistency of the measurements. Once we know a , b , c , and f , we calculate the field $E = -\nabla V$ and the gradient of E^2 . We find

$$\frac{\partial E^2}{\partial x} = 2(4c^2 + f^2)x + 2bf + 4ac$$

$$\frac{\partial E^2}{\partial y} = 2(4c^2 + f^2)y + 2af - 4bc$$

$$F_0 = |\nabla E^2| = \left[\left(\frac{\partial E^2}{\partial x} \right)^2 + \left(\frac{\partial E^2}{\partial y} \right)^2 \right]^{1/2}$$

This quantity is shown on Figs. 7a, 7b, and 7c for points located on the same chord of the circle made by the outer electrode.

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